

# Single-phase and boiling liquid jet impingement cooling in power electronics

**Sreekant Narumanchi**

**Email: [sreekant\\_narumanchi@nrel.gov](mailto:sreekant_narumanchi@nrel.gov)**

**Phone: 303-275-4062**

**National Renewable Energy Laboratory**

**FY05 Budget: \$300K**

**FY06 Budget: \$300K**

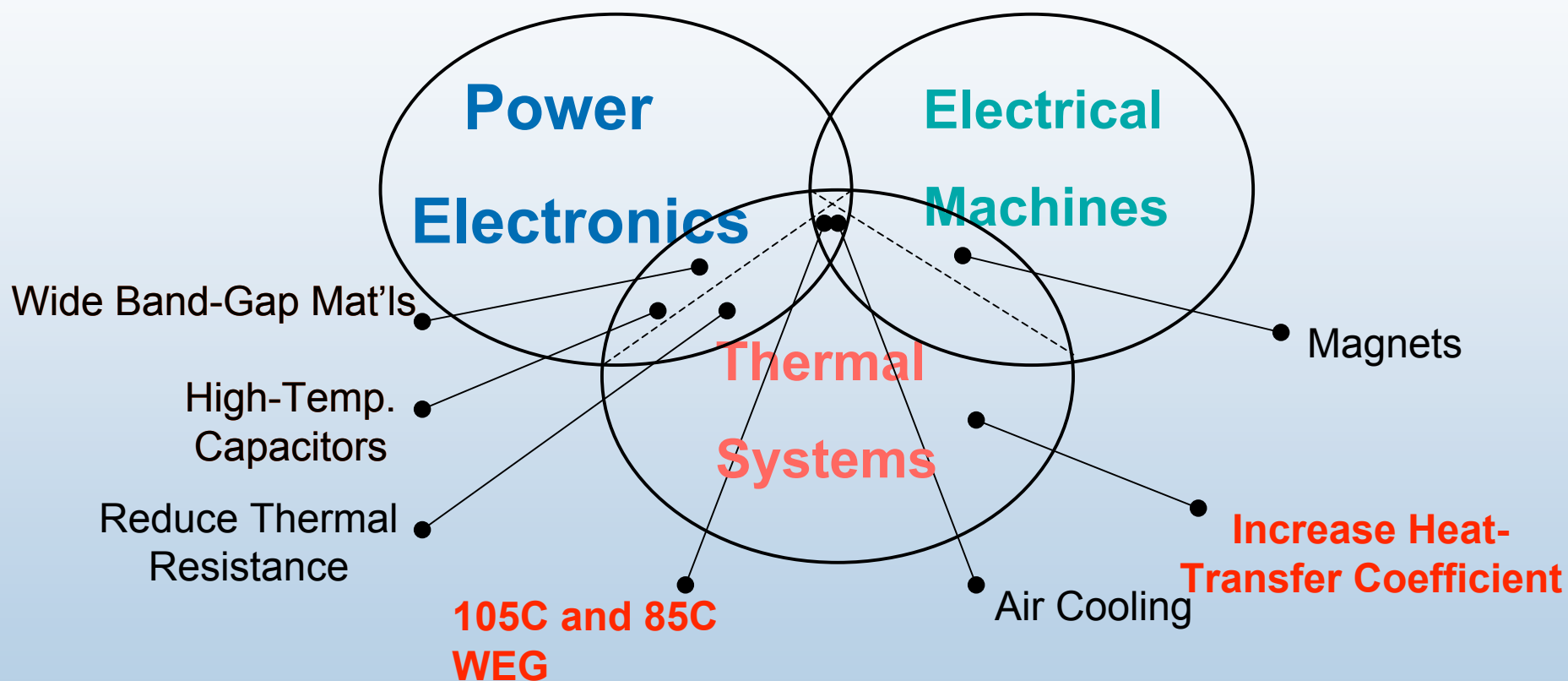
**Project Duration: FY05 to FY07**

FreedomCAR APEEM FY05 Wrap-up/FY06 Kick-off Meeting  
Oak Ridge National Laboratory  
National Transportation Research Center

November 1, 2005



# Where Does This Project Fit?



# What is This Project?

- Thermal management of power electronics components (e.g. IGBTs)
- Exploring liquid jet impingement cooling
  - Different impingement configurations
  - Single-phase and boiling jets
  - Empirical correlations
  - CFD simulations
  - Experiments on prototype structure
  - Heat transfer enhancements
  - Experimental demonstration on an inverter

# Technical Approach

- Empirical correlations for both single-phase and boiling jets
- CFD simulations of single-phase and boiling jets
- Experimental validation of CFD simulations with existing experimental data
- IGBT package simulations for both single-phase jets (with water and glycol-water mixture) and boiling jets (with water)

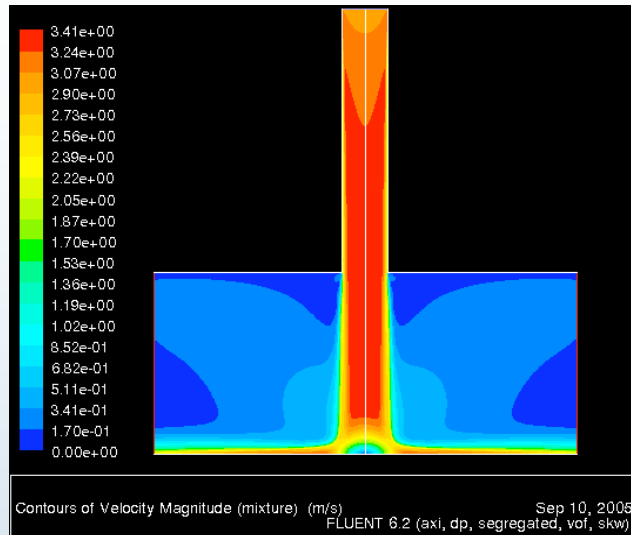
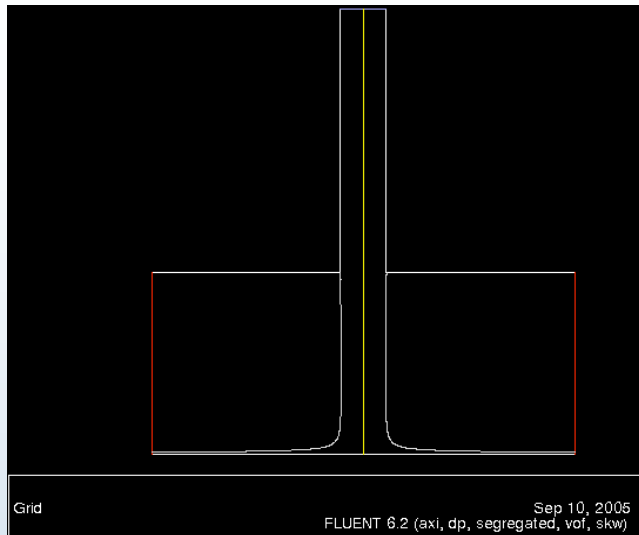
# Goal

- Establish a liquid cooling solution which dissipates up to  $200 \text{ W/cm}^2$  from the silicon die in the IGBT package
- Preferably use glycol-water mixture at  $105 \text{ C}$  inlet temperature in the single-phase regime
- Maintain the maximum temperature in the silicon die below  $125 \text{ C}$

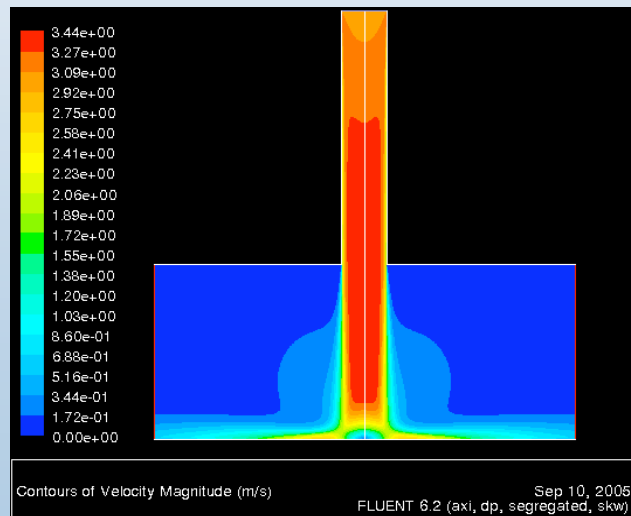
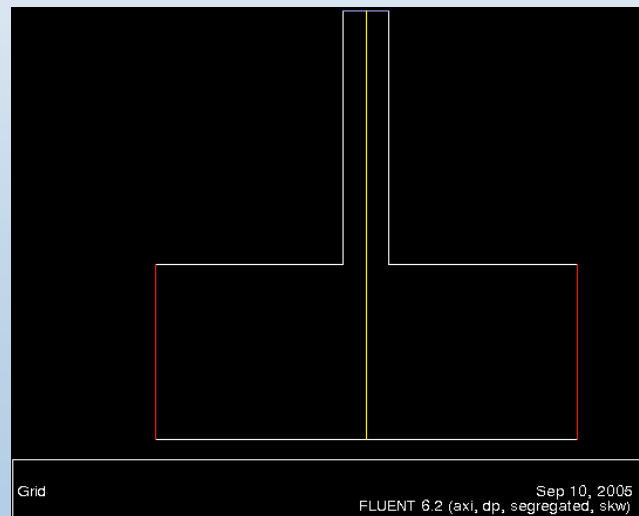
# Approach and accomplishments for FY05

- User defined function (UDF) for nucleate boiling has been implemented and customized in the CFD code FLUENT for jet impingement applications
- A spreadsheet-based modeling tool, based on empirical correlations, for both single-phase and boiling jets has also been developed
- Numerical simulations also performed to study jet impingement cooling of IGBT package (Semikron inverter)
  - Baseline conditions demonstrated under which the program goals can be met with single-phase glycol-water jets

# Different jet configurations

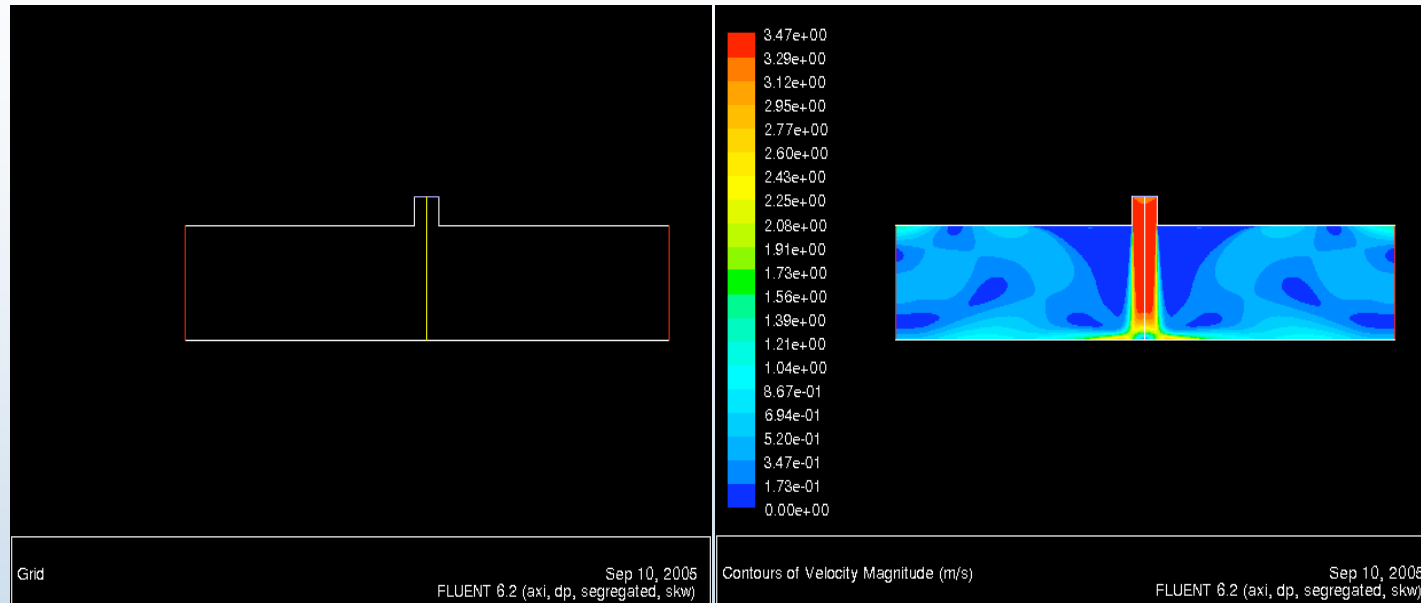


Free-surface jet  
(Womac et al.,  
1993)  
configuration



Submerged jet  
(Womac et al.,  
1993)  
configuration

# Different jet configurations



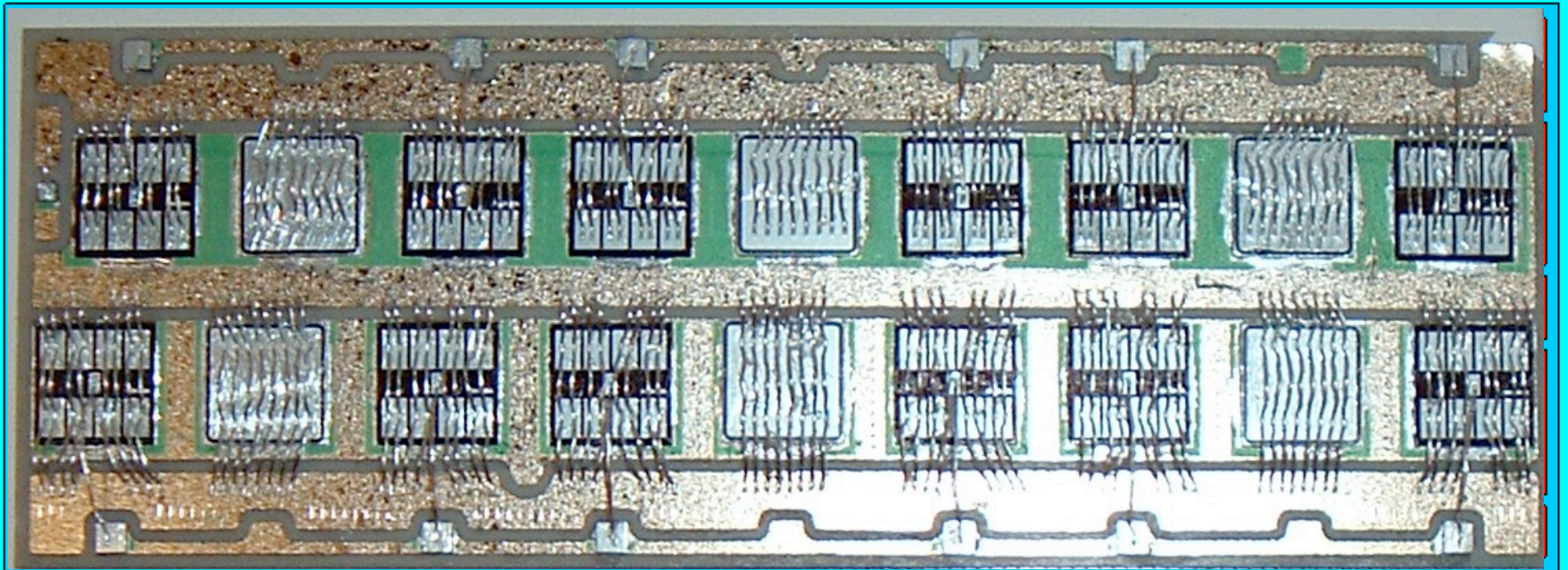
Confined submerged jet (Garimella and Rice, 1995) configuration



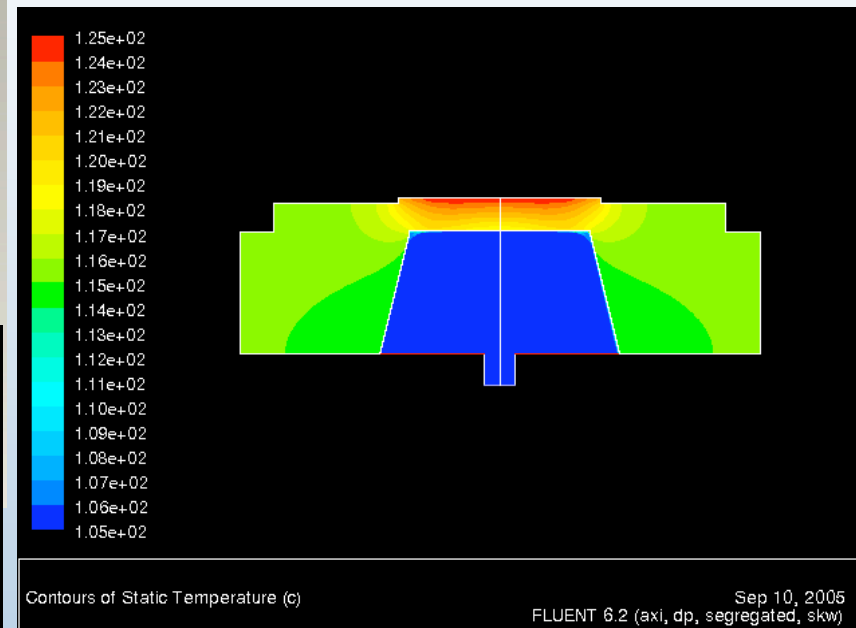
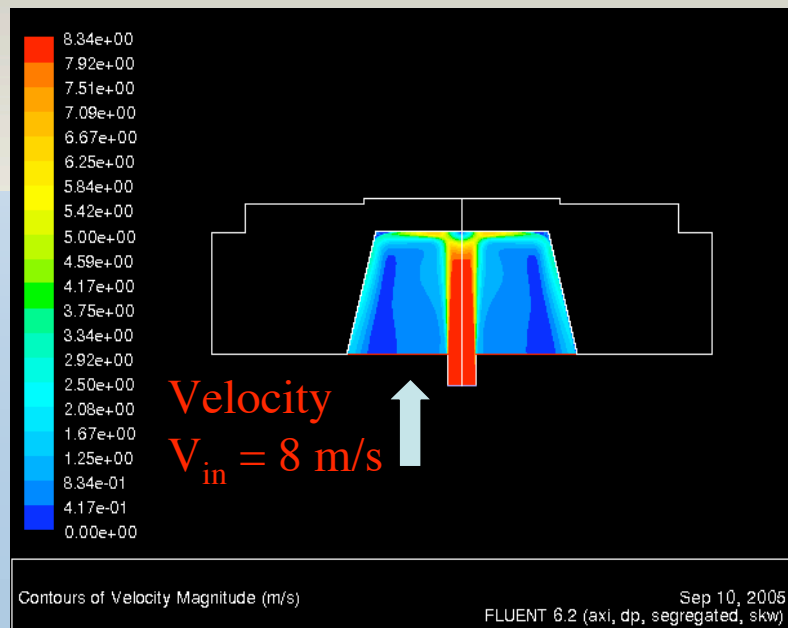
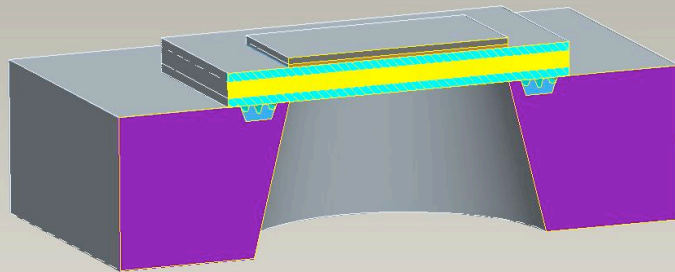
# Comparison between CFD results and experimental results

Configuration	Problem parameters	$h_{avg}$ from correlations (W/m <sup>2</sup> K)	$h_{avg}$ from Fluent (W/m <sup>2</sup> K)	% difference between Fluent and correlation
Single circular submerged jet (Womac et al. 1993)	$v=3$ m/s, $d=3.1$ mm, $S_{NP}=4d$ , $Re_d=9300$	27300	26400	3
	$v=15$ m/s, $Re_d=46400$	69300	81400	16
Single circular free-surface jet (Womac et al. 1993)	$v=1$ m/s, $d=3.1$ mm, $S_{NP}=4d$ , $Re_d=3100$	11500	14000	20
	$v=3$ m/s, $Re_d=9300$	19600	22500	14
	$v=15$ m/s, $Re_d=46400$	45700	61000	29
Single circular submerged and confined jet (Garimella and Rice 1995)	$v=1.3$ m/s, $d=3.18$ mm, $S_{NP}=4d$ , $Re_d=4100$	18300	19200	5
	$v=3.27$ m/s, $Re_d=10300$	34800	34800	0
	$v=7.0$ m/s, $Re_d=22100$	59100	54500	8

# Half bridge with IGBTs



# Low thermal resistance IGBT structure simulation



Temperature contours  
 $90 \text{ W/cm}^2$ ;  $T_{\max} = 125^\circ\text{C}$ ;  $T_{\text{coolant}} = 105^\circ\text{C}$   
 (Glycol-Water mixture)

# Heat transfer results for the different cases

	GLYCOL-WATER MIXTURE		WATER	
	90 W/cm <sup>2</sup>	2 0 0 W/cm <sup>2</sup>	90 W/cm <sup>2</sup>	200 W/cm <sup>2</sup>
Jet velocity, m/s	8	20	8	20
T <sub>INLET</sub> , °C	105	105	105	105
T <sub>MAX</sub> , °C	125	135	119	127
h <sub>COPPER</sub> , W/m <sup>2</sup> K	39,000	75,700	74,200	157,300
h <sub>ALUMINUM</sub> , W/m <sup>2</sup> K	19,800	40,500	37,100	76,500

12

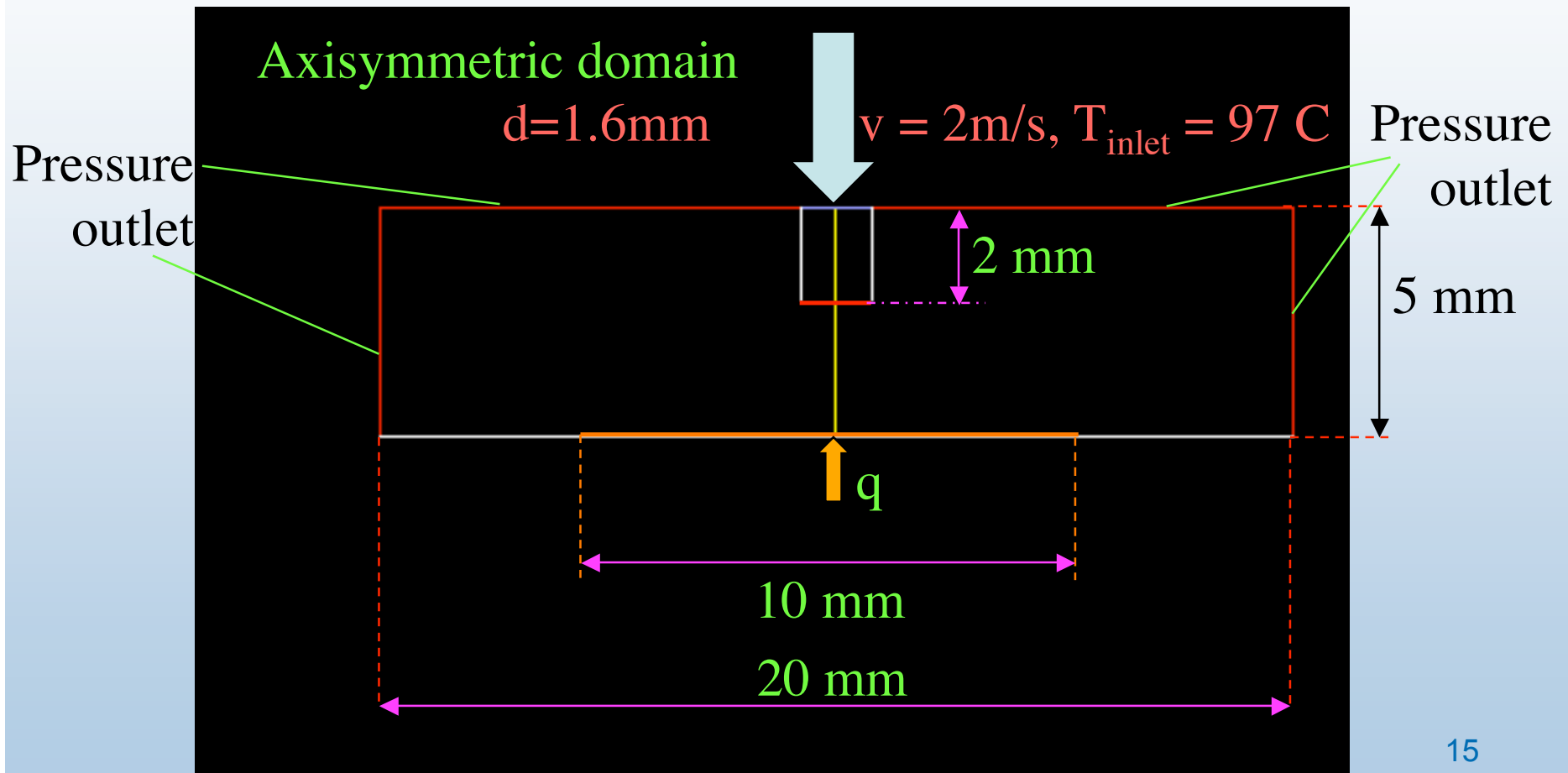
# Summary for single phase jets

- CFD predictions compare well with available experimental data in the literature for submerged jets
- Glycol-water jet impingement simulation of the low thermal resistance IGBT structure reveals
  - $q = 90 \text{ W/cm}^2$ ;  $v = 8 \text{ m/s}$ ;  $T_{\text{inlet}} = 105^\circ\text{C}$ ;  $T_{\text{max}} = 125^\circ\text{C}$
  - $q = 200 \text{ W/cm}^2$ ;  $v = 20 \text{ m/s}$ ;  $T_{\text{inlet}} = 105^\circ\text{C}$ ;  $T_{\text{max}} = 135^\circ\text{C}$
- With surface enhancements and pulsating/self-oscillating jets, there is a potential for removing 150 to  $200 \text{ W/cm}^2$  with velocities less than  $10 \text{ m/s}$

# Numerical (CFD) simulations of nucleate boiling in turbulent impinging jets

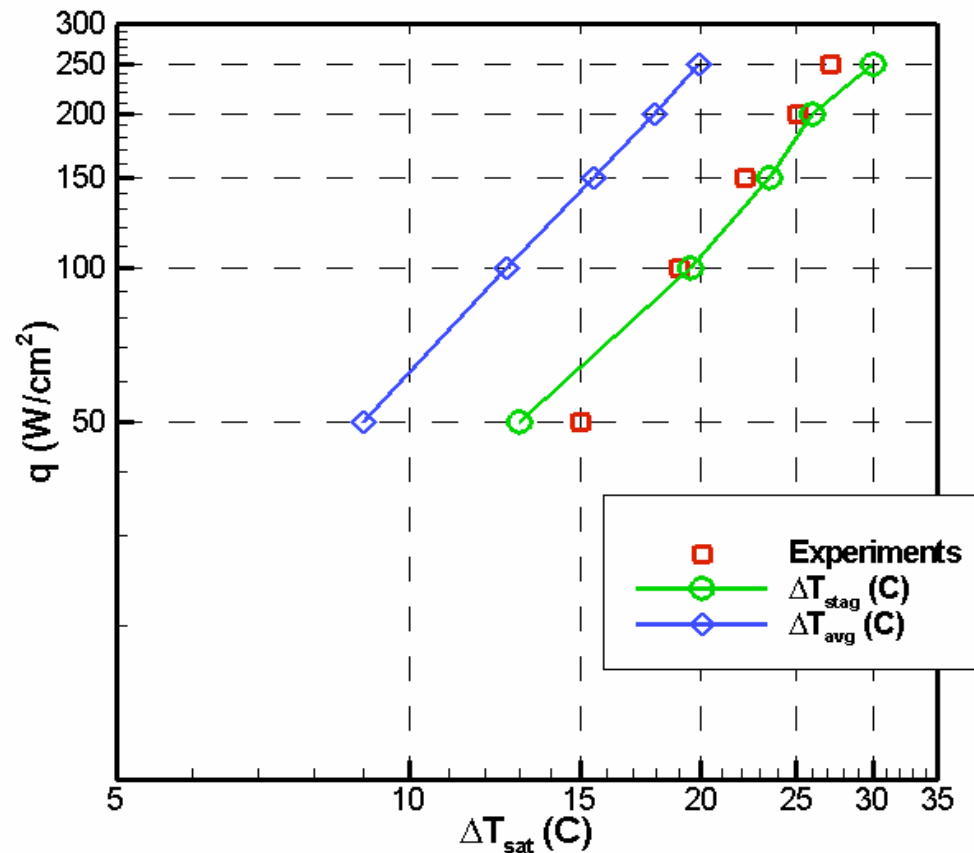
- Based on the Eulerian multiphase model proposed by Podowski et al. (1997)
  - This involves numerically solving the mass, momentum and energy conservation equations for different phases
  - A number of closure relations for interfacial terms between liquid and vapor
- User defined function (UDF) for nucleate boiling in impinging jets has been customized and implemented in FLUENT

# Validation with experimental study of Katto and Kunihiro (1973) with submerged water jets



# Comparison of boiling curve obtained from experiments and CFD

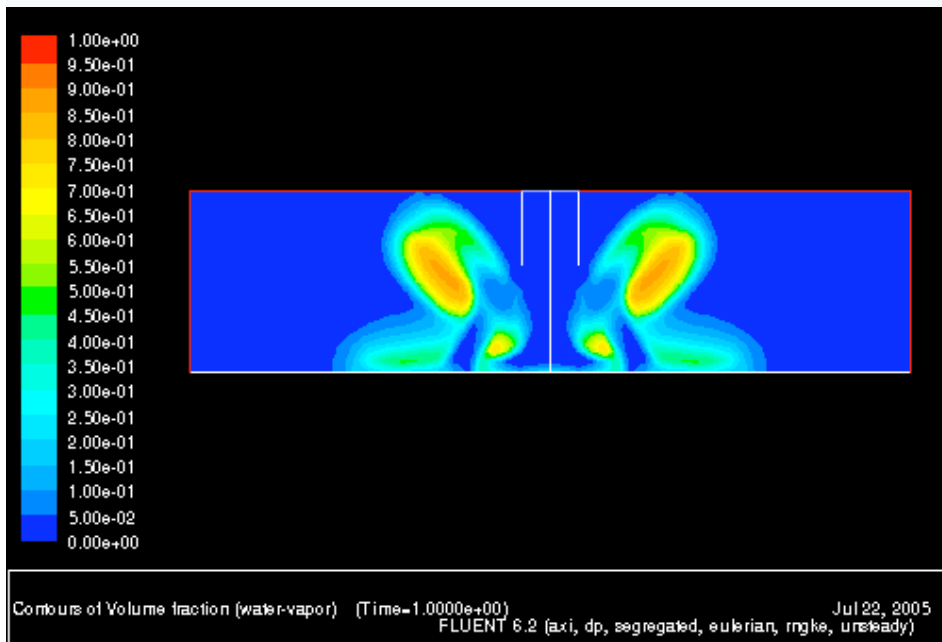
First time  
a CFD code is  
being validated  
with this  
experimental  
data



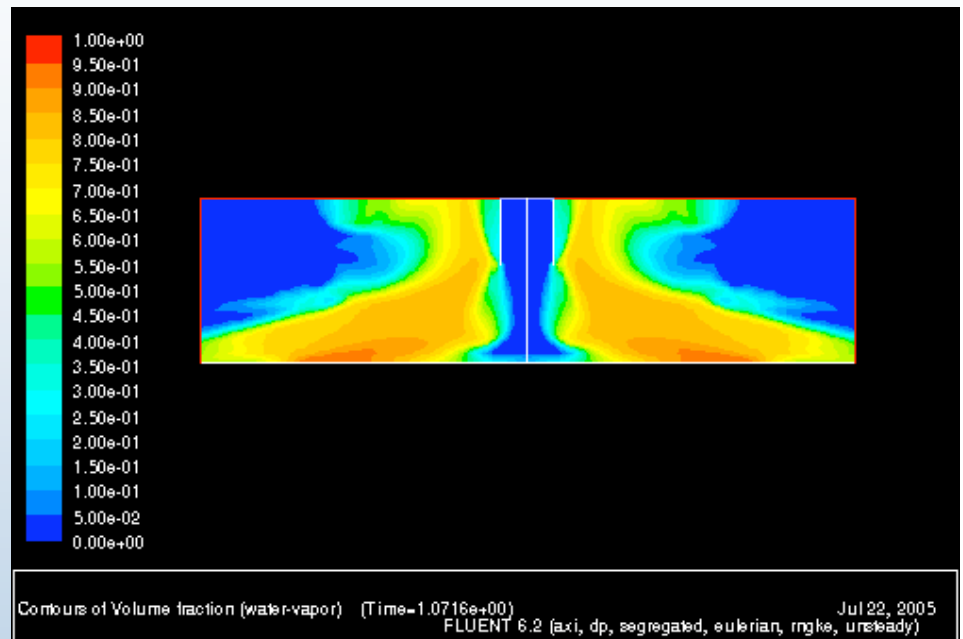


# Animations of vapor formation

50 W/cm<sup>2</sup>

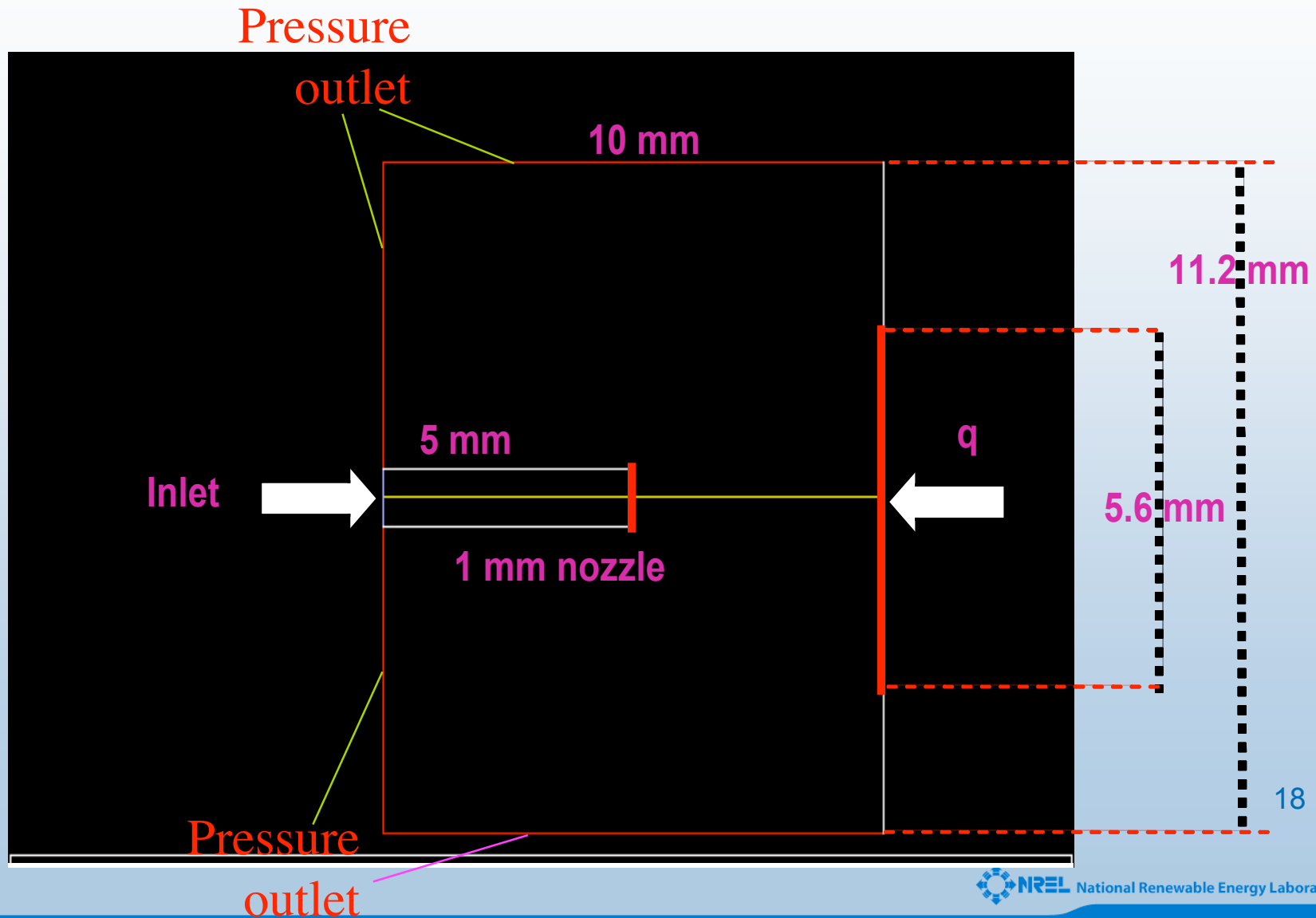


100 W/cm<sup>2</sup>

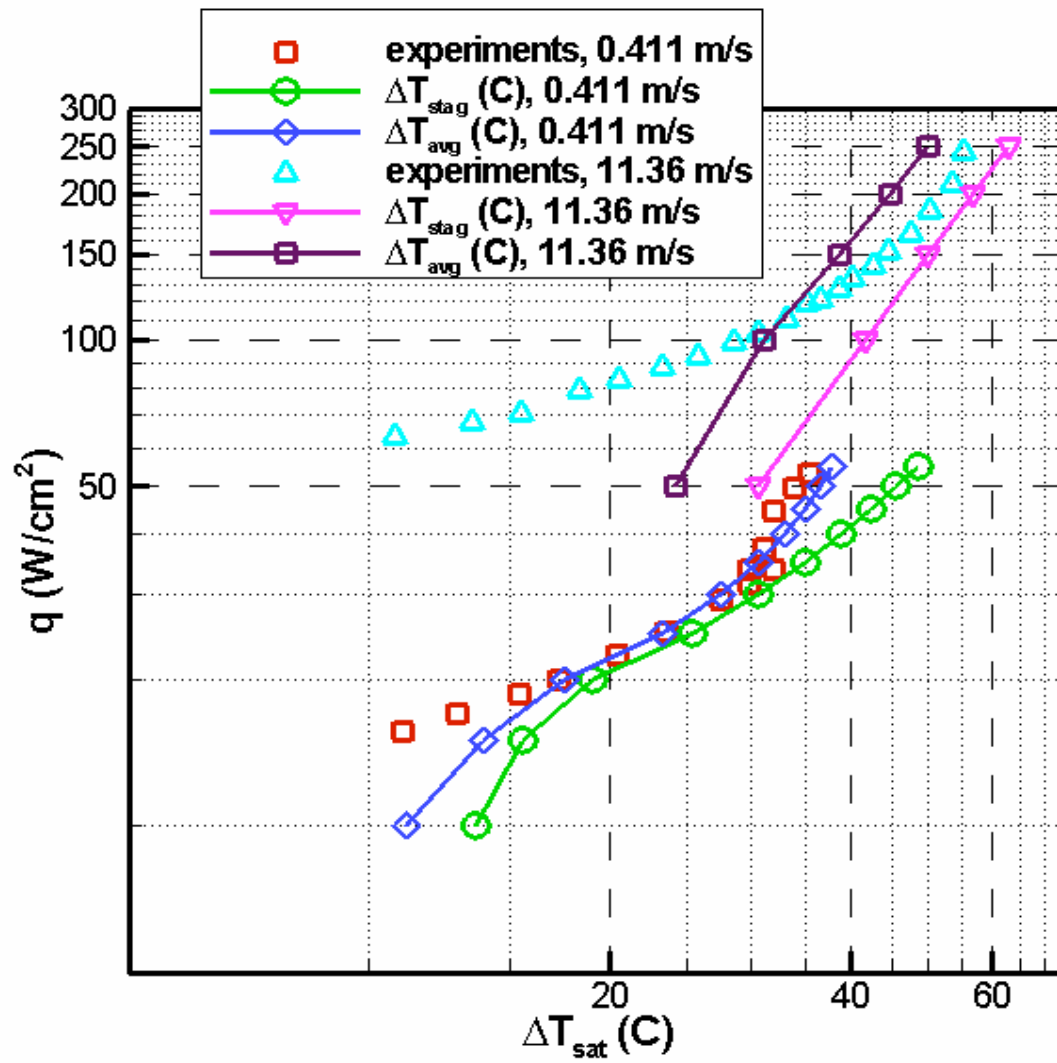


Water jet;  $d=1.6\text{mm}$ ;  $v = 2\text{m/s}$ ;  $T_{\text{inlet}} = 97\text{ C}$ ;  $T_{\text{sat}} = 100\text{ C}$

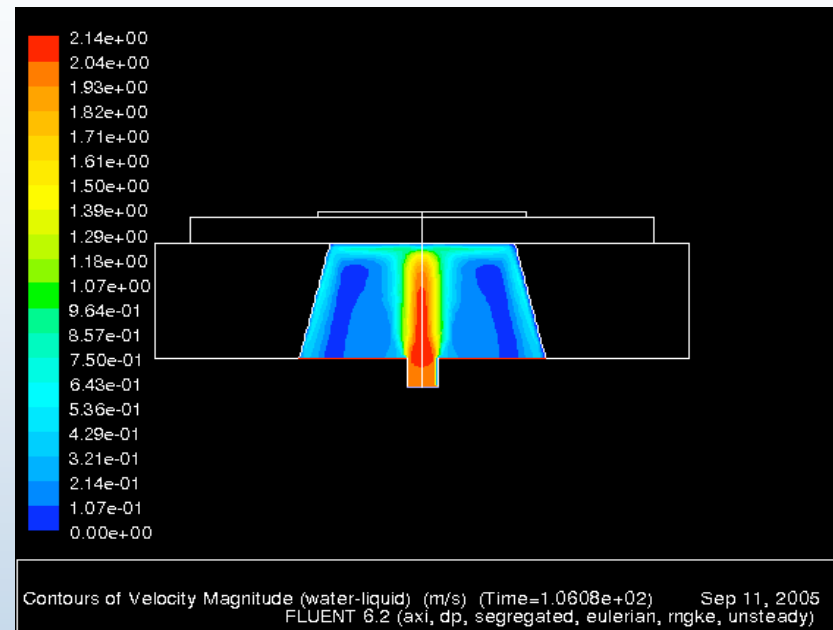
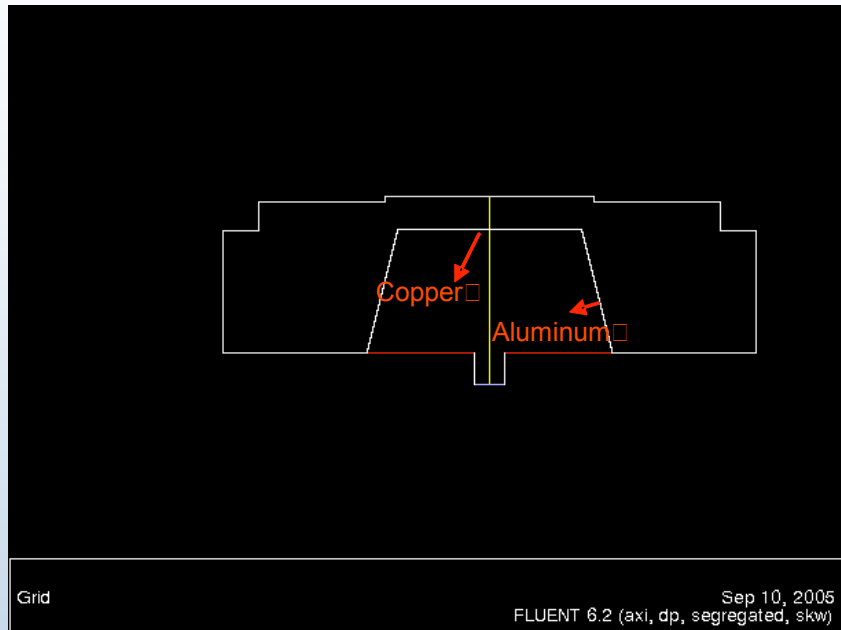
## Validation with experimental results of Zhou and Ma (2004) for submerged R113 jets



# Comparison of boiling curve obtained from experiments and CFD



# Numerical simulations of IGBT package cooling with boiling jets



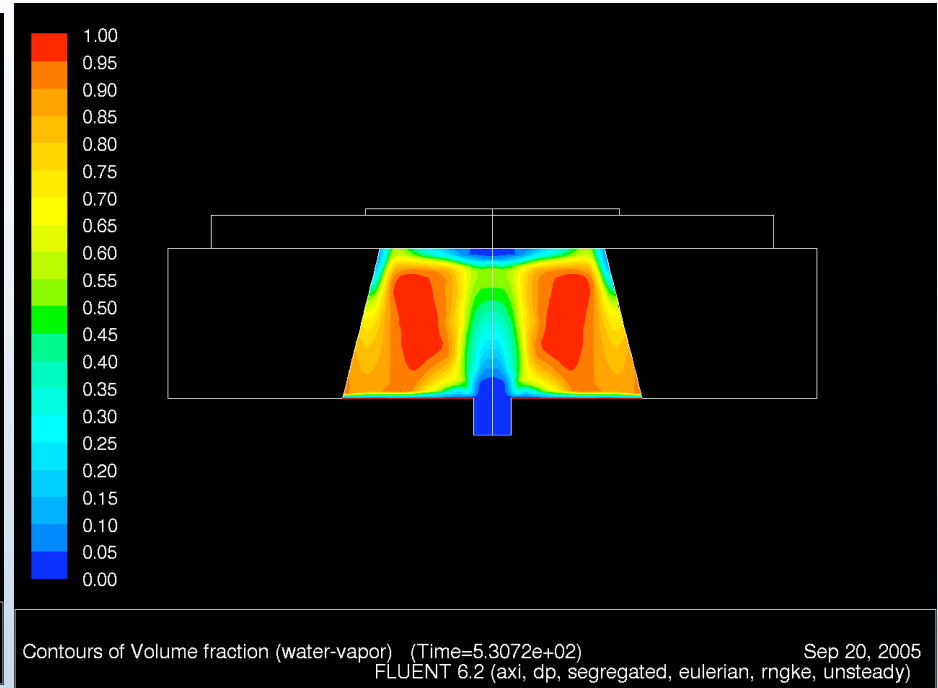
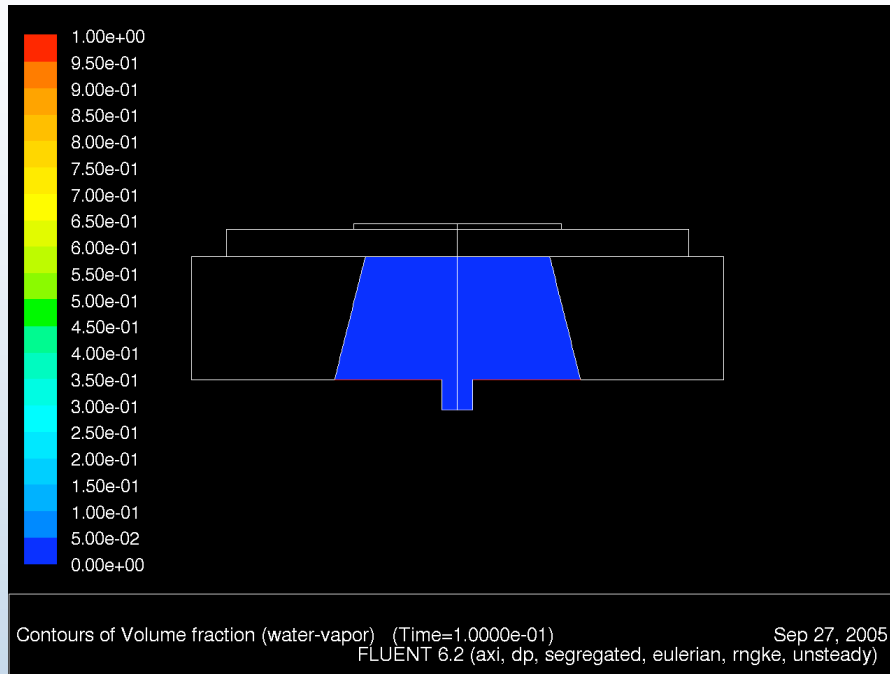
Water jet;  $T_{\text{inlet}}=105\text{ C}$ ;  $T_{\text{sat}}=108\text{ C}$ ;  $v=2\text{ m/s}$

Heat dissipation in the silicon die

# Animations of vapor volume fraction

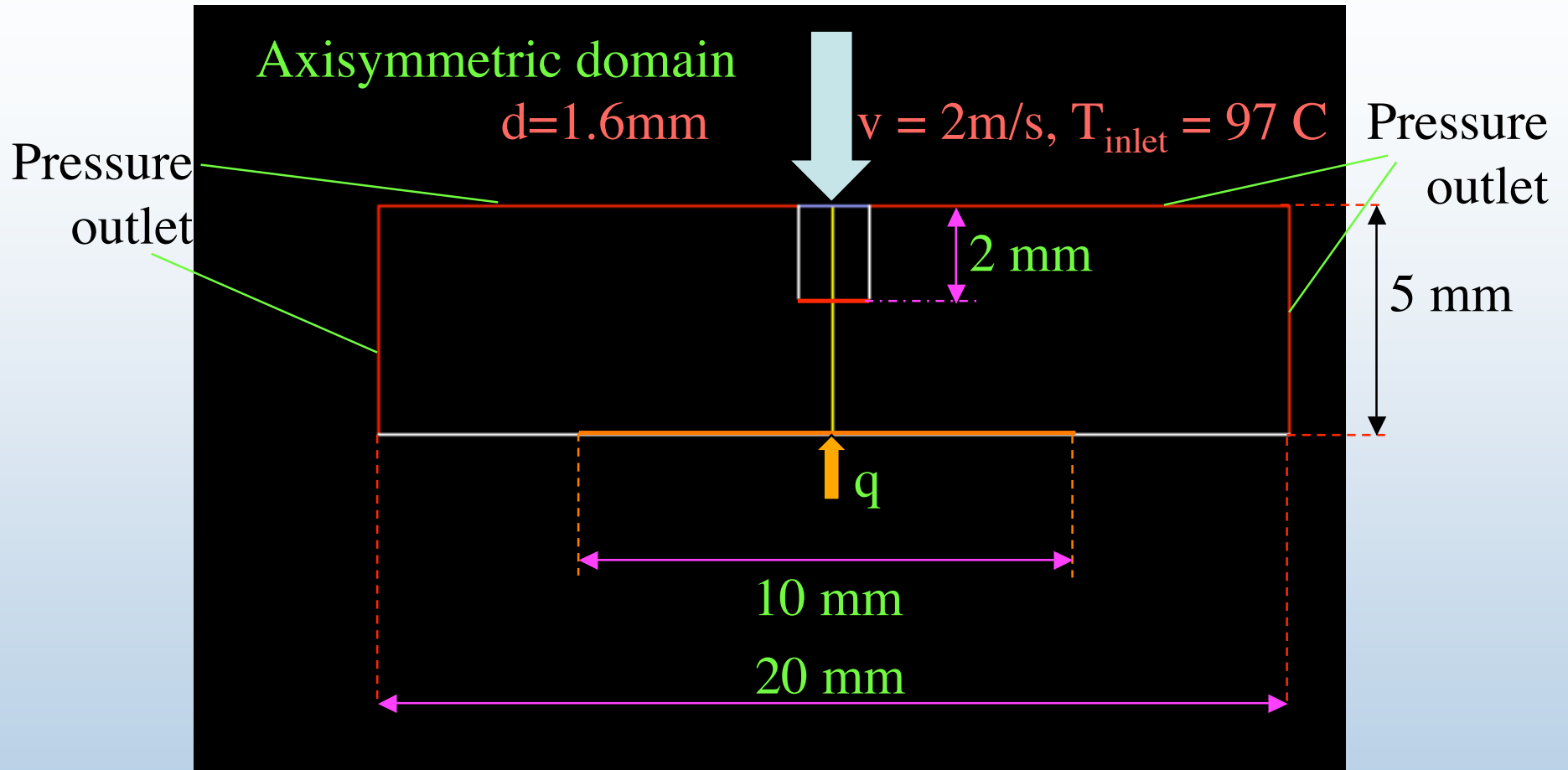
45 W/cm<sup>2</sup>

90 W/cm<sup>2</sup>



Water jet;  $T_{\text{inlet}}=105$  C;  $T_{\text{sat}}=108$  C;  $v=2$  m/s

# Impact of boiling



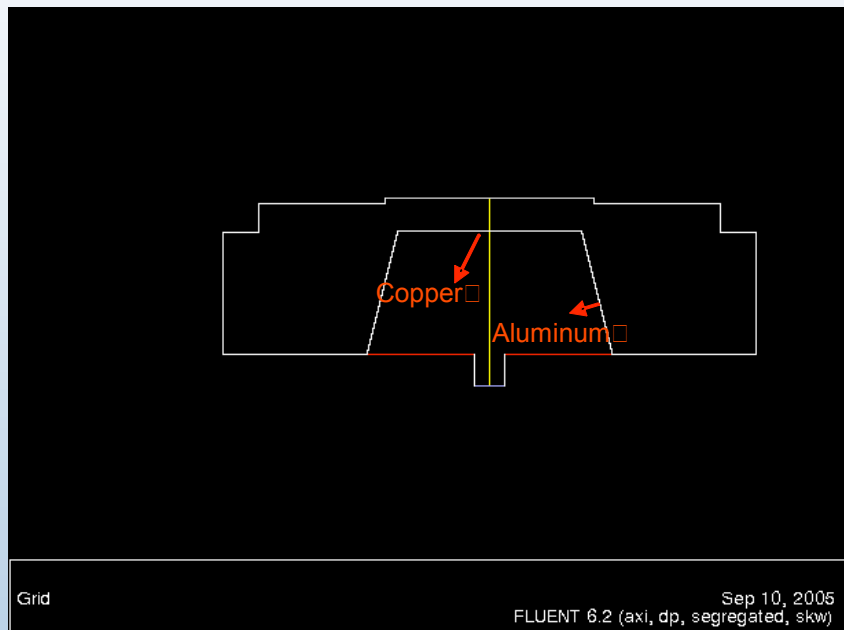
$$q = 100 \text{ W/cm}^2$$

$$T_{\text{wall}_{\text{avg}}} = 113 \text{ C (with boiling)}$$

$$T_{\text{wall}_{\text{avg}}} = 135 \text{ C (without boiling)}$$

# Impact of boiling

Water jet;  $T_{\text{inlet}}=105\text{ C}$ ;  $T_{\text{sat}}=108\text{ C}$ ;  $v=2\text{ m/s}$



$$q = 45\text{ W/cm}^2$$

$$T_{\text{wall}_{\text{avg}}} = 121.5\text{ C (with boiling)}$$

$$T_{\text{wall}_{\text{avg}}} = 123.4\text{ C (without boiling)}$$

$$q = 90\text{ W/cm}^2$$

$$T_{\text{wall}_{\text{avg}}} = 139.3\text{ C (with boiling)}$$

$$T_{\text{wall}_{\text{avg}}} = 142.0\text{ C (without boiling)}$$

# Summary and conclusions for boiling jets

- UDF for nucleate boiling has been customized for jet impingement applications and implemented in FLUENT
  - Code has been validated against experimental data
- The impact of boiling has been explored
- Saturated fluorinerts (FC72, 77, 84) and OS-10 yield low critical heat fluxes (CHF) ( $< 60 \text{ W/cm}^2$  for velocities as high as 8 m/s). Water yields highest CHF values
  - An appropriate working fluid in the boiling regime for power electronics applications needs to be investigated



# Project motivation for FY06

- Glycol-water mixture will be readily accepted as a working fluid in the single-phase regime
- Very high velocities would be required to meet program requirements with single-phase jets
- Enhancements in heat transfer need to be explored
- Self-oscillating/pulsating jets and surface enhancements have the potential to enhance the heat transfer coefficients considerably ( $\sim 100\%$ )

# Approach for FY06

- Explore single-phase glycol-water jets with enhancements in heat transfer
- Visualization tests with self-oscillating nozzles obtained from a company
- Experiments on a prototype structure (heat transfer)
- After data analysis and proof of enhancements, plan for tests in an actual inverter

# Animations of self-oscillating jets



27

# Timeline for FY06

FY06 Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Complete all visualization tests											
	Tests with the prototype structure and self-oscillating jets (25%)										
		Tests with the prototype structure and self-oscillating jets (50%)									
				Tests with the prototype structure and self-oscillating jets (100%)							Annual report
					Identify optimum configuration						
							Plan/start tests on an inverter				

28

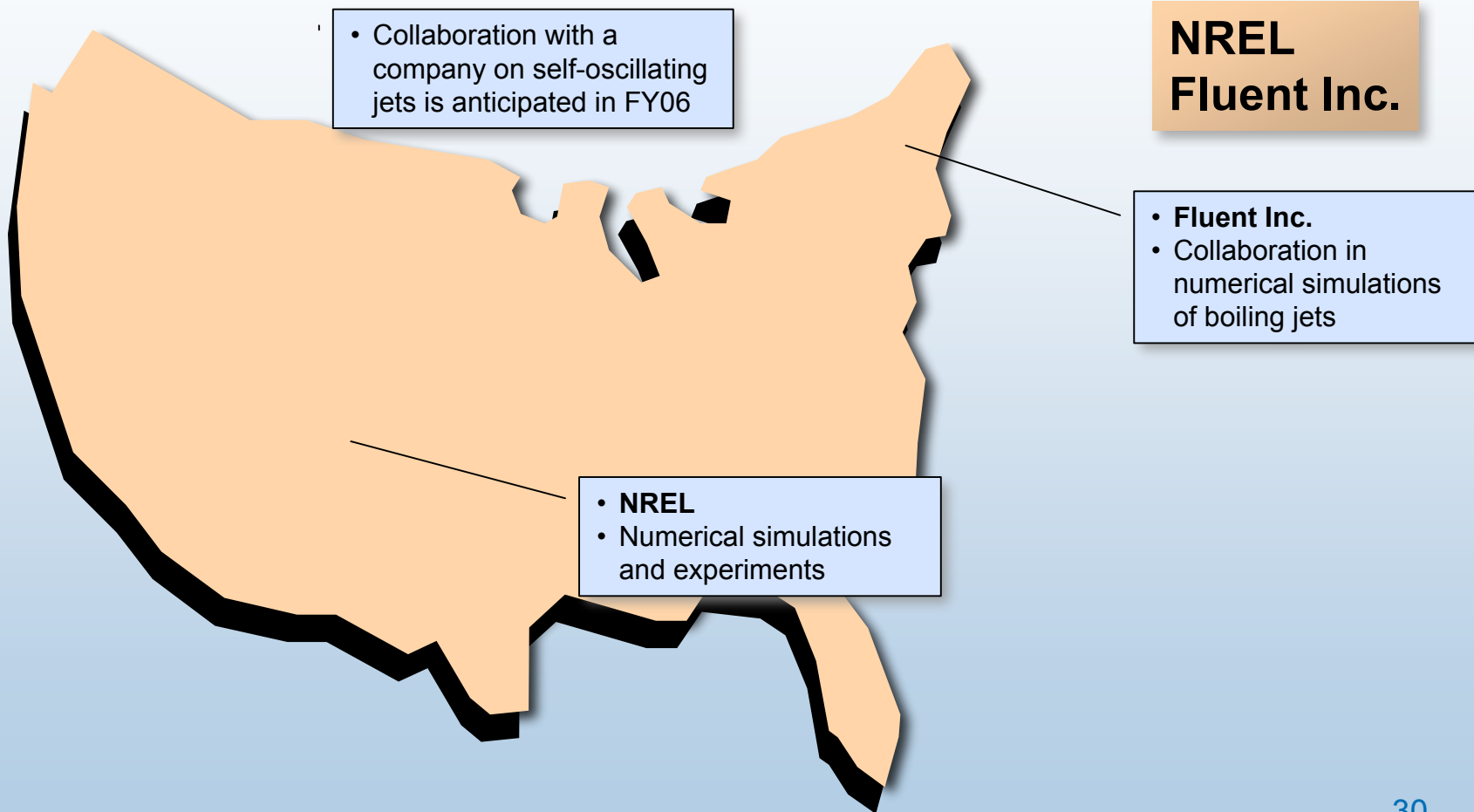
Key task

Milestone/  
Deliverable

# Barriers/Challenges

- Issues related to erosion and package stresses may have to be addressed
- The reliability of the jet impingement cooling system will have to be demonstrated

# Interactions and Collaborations



# Questions

